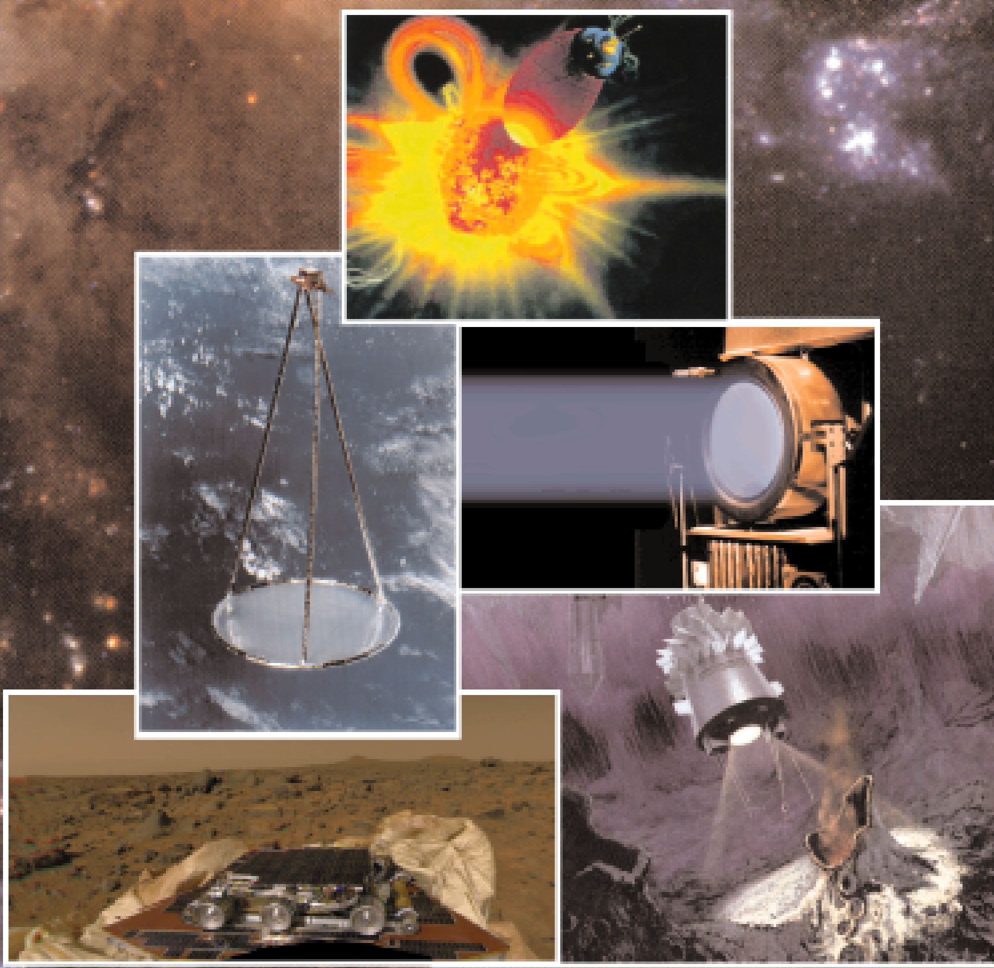
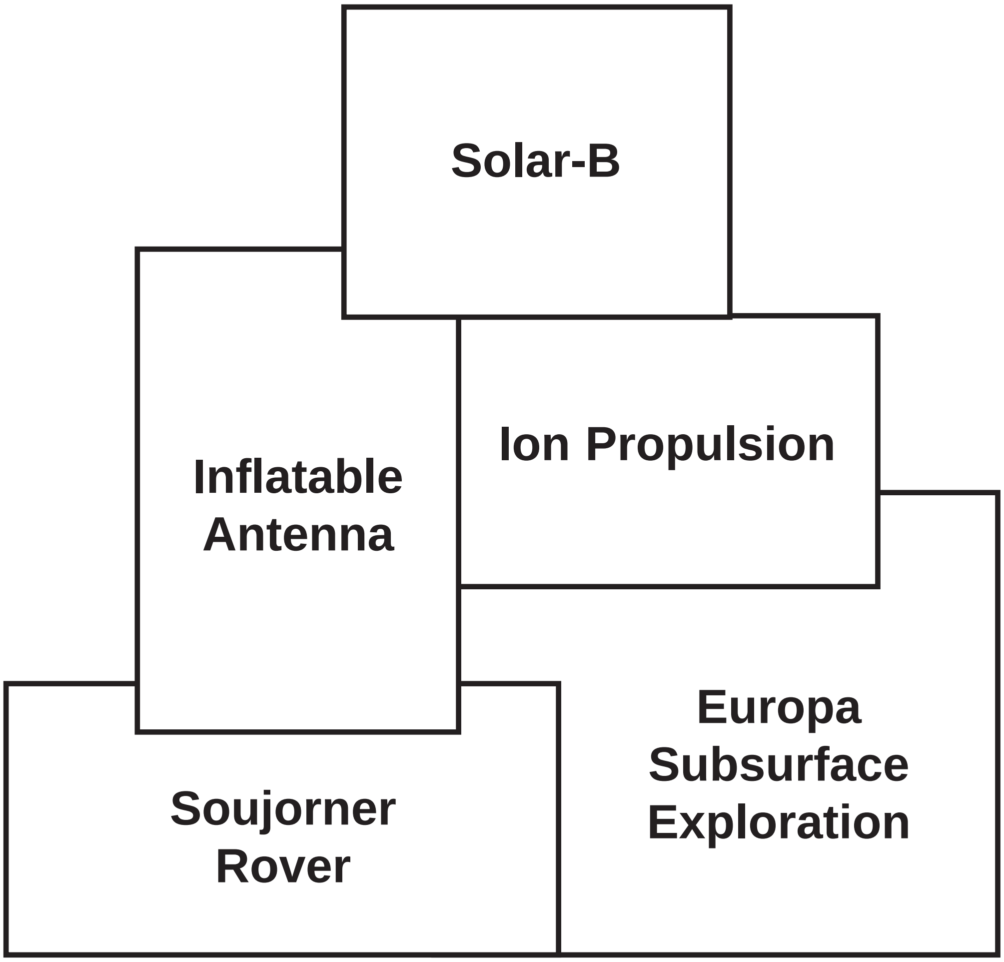
The Space Science Enterprise Integrated Technology Strategy



October 1998

To research, develop, verify, and transfer technologies



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The Office of Space Science (OSS) pursues an Integrated Technology Strategy that supports NASA strategic planning. Space science technology development will: (1) support the advancement and communication of scientific knowledge and understanding; (2) enable the exploration, use, and development of space; and (3) research, develop, verify, and transfer advanced aeronautics, space, and related critical technologies required to enhance space exploration, expand our knowledge of the universe, and ensure continued national scientific, technical, and economic leadership.

NASA is improving efficiency and focusing its efforts. Technology is seen as the pivotal element in achieving the space science goals of significantly reduced spacecraft development cost and time and an increased annual flight rate as shown in Figure 1. New technology is critical in enabling the new levels of performance and capability required by the current set of planned space science missions.

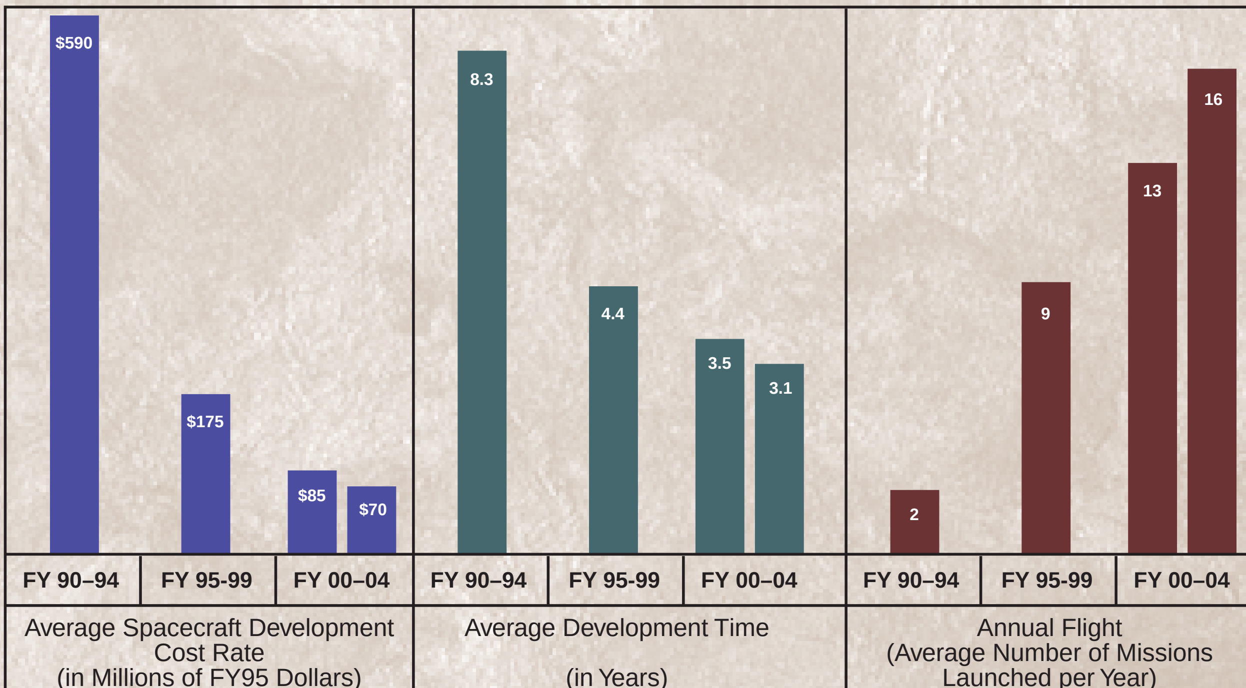


Figure 1. Total NASA Earth and Space Science

To meet these new challenges, our technology plan and policy must be *integrated* across all elements supporting space science missions as well as with those supporting other NASA Enterprises. As budgets continue to be flat and the performance required continues to rise, any inefficiencies or redundancies adversely affect the ability to satisfy the technology needs of the future science missions. In addition, plans of other Government agencies, such as the Department of Defense (DOD), the Department of Energy (DOE), the National Oceanic and Atmospheric Administration (NOAA), and others, must also be considered and coordinated as similar pressures impact those agencies.

TECHNOLOGY STRATEGY

Technology Program Pillars

- **An aggressive, long-range core technology program to enable the next generation of high-performance and cost-effective Space Science missions**

- **A solid, mainstream set of focused technology programs to enable near-term emerging missions**

- **A flight validation program, complemented by advanced development to bring laboratory pre-prototypes to flight readiness**

- **A far-reaching mission studies and advanced concepts program to explore the full range of near- and long-term mission options and how to achieve them**

A central element of the overall Space Science Integrated Technology Strategy is to develop new capabilities and innovative technology that will enable us to meet the challenges of the 21st century. The missions proposed by OSS must be accomplished within fixed budgets that are dramatically lower than those of past generations of missions. In many cases, they require fundamentally new observational and measurement techniques.

The new prominence of technology development is a key part of the fundamental changes in the Space Science Enterprise. OSS has adopted a flexible strategy in which missions are flown when technology development allows us to best meet the objectives for a fixed low cost. In this approach, mission and technology planning proceed together from the outset, with both sides working to achieve a balance of cost, performance, and schedule (Figure 2).

OSS Technology Goals

1. Lower mission life-cycle costs and provide critical new capabilities through aggressive technology development.
2. Develop innovative technologies to address far-term scientific goals, spawn new measurement concepts and mission opportunities, and create new ways of doing space science.
3. Develop and nurture an effective science-technology partnership to help optimize mission concepts and infuse new technologies into science missions, with the goal of dramatically lowering mission cost and risk.
4. Stimulate cooperation among industry, academia, and Government to ensure that the Nation can reap the maximum scientific and economic benefit from its space science mission and technology programs.
5. Identify and fund the long-range strategic technologies that have broad potential to span the needs of more than one NASA Enterprise.

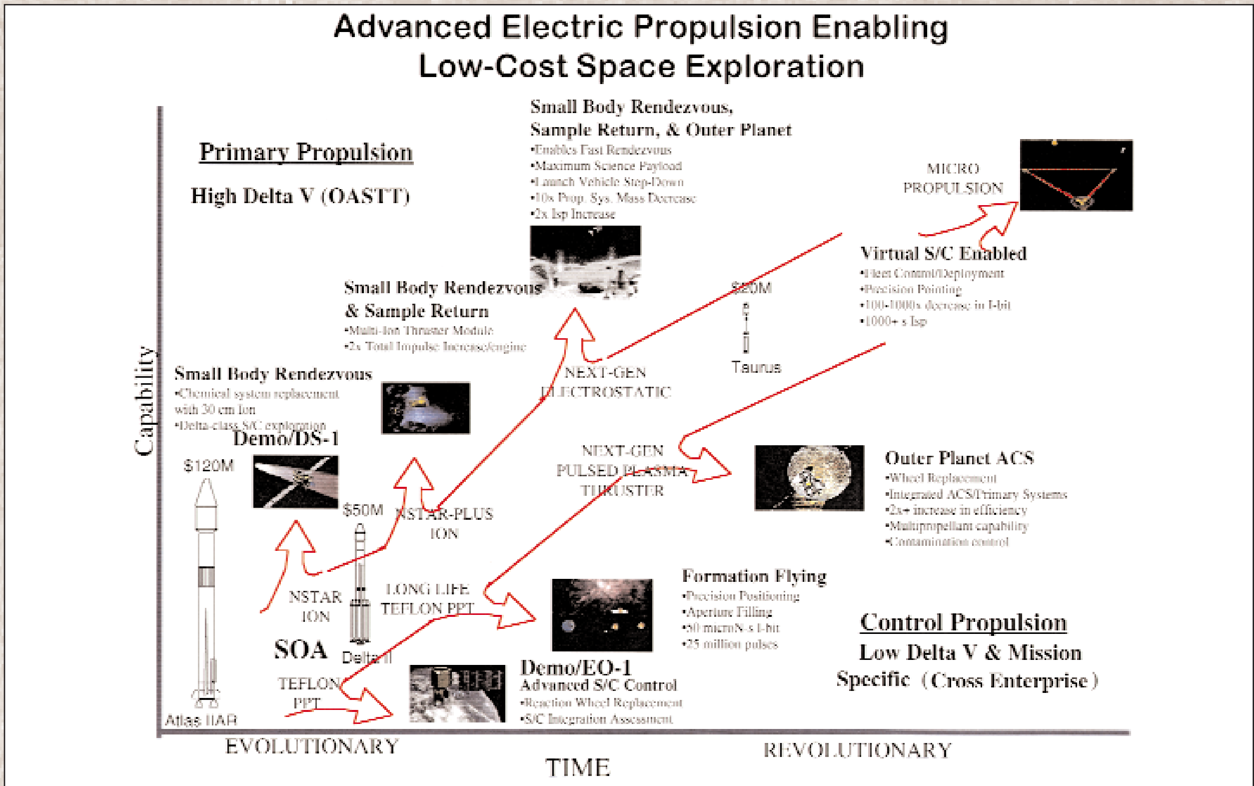


Figure 2. Advanced Electric Propulsion Enabling Low-Cost Space Exploration

TECHNOLOGY PROGRAM ORGANIZATION

- **Advanced Concepts Program**
  conducts studies and proof-of-concept efforts for far-term (10 to 25 years) technology

- **Cross-Enterprise Technology Program**
  develops long-range (5 to 10 years) strategic crosscutting technologies that show broad potential across multiple NASA Enterprises

- **Space Science Core Program**
  develops mid- and far-term technologies for the Space Science Enterprise

- **Space Science Focused Programs**
  develops Space Science Enterprise mission-specific technology areas in the current OSS Strategic Plan

- **Flight Validation**
  completes the technology development process by validating technologies in space

III

The Space Science Enterprise technology program is organized into five elements: an Advanced Concepts Program, a Cross-Enterprise Technology Development Program, a Space Science Core Technology Program, several focused technology programs, and a Flight Validation Program.

1. The **Advanced Concepts Program** conducts research and tests hypotheses for far-term (10–25 years) technology. This program consists of two principal efforts.

   One is to elicit and develop highly innovative, specific far-term ideas into feasible technological concepts that provide imaginative options for future space endeavors. These options may either (a) expand the envelope for strategic goals and objectives or (b) expand the "toolkit" of future mission capabilities (Figure 3).

Figure 3. Laser Power Beaming for Jupiter Scientific Station

   The second effort focuses on creating a climate in which highly unconventional, visionary approaches and ideas are more effectively infused into the mission and technology communities. This involves (a) developing new strategic and technological visions and architectures that stem from anticipating unprecedented technological capabilities of the future and (b) developing "cutting-edge" tools, processes, and techniques for generating, infusing, and adopting advanced concepts.

   The advanced concepts process steps are based on the scientific method of research: problem formulated, information collected, hypothesis proposed, and finally hypothesis tested and results reported. The last step is essentially the same as the Technology Readiness Level (TRL) 1, "Basic Principles Observed and Reported," in the technology programs, as shown in Figure 12. Successful new concepts are fed into the lowest TRLs of the technology programs described below.

2. The **Cross-Enterprise Technology Development Program** supports technology requirements for all NASA space Enterprises, focusing on developments supporting multiple Enterprise customers (see Appendix A). These developments tend to focus on the earlier stages of the technology life cycle. Emphasis is on basic research into physical principles, formulation of applications concepts, and component-level performance evaluation. Where appropriate, these developments may extend all the way to subsystem-level development for missions, with joint development and funding from customer Enterprise (Figure 4).

Figure 4. Electric Ion Propulsion: Subsystem Technology Supporting Multiple NASA Enterprises

3. The **Space Science Core Technology Program** supports mission-specific technologies for the Space Science Enterprise. It is similar to the Cross-Enterprise Technology Development Program, except that it specifically supports OSS requirements. The Core Technology Program supports enabling technologies for the next generation of high-performance and cost-effective Space Science Enterprise missions. The program attempts to retire technological risk early in the mission design cycle, while emphasizing innovation to reach previously unattainable goals in mass reduction and performance, which are key to the success of many of the Space Science missions planned for the next century (Figure 5).

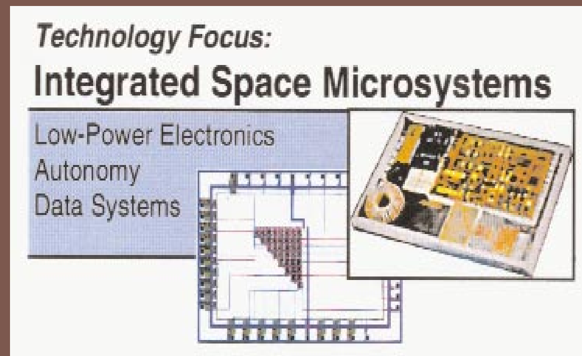


Figure 5. Advanced Deep Space System Development

4. Several **focused programs** are dedicated to specific high-priority technology areas in support of the Space Science Enterprise Strategic Plan. They are driven by the needs of the Space Science Enterprise, but other Enterprises are likely to benefit from them. There are presently five focused programs:

   - **Solar System Exploration Technology.** This program will develop critical technologies for the Mars Surveyor program. Critical technologies include those supporting planetary ascent propulsion, sample selection and return, planetary protection, and planetary and small body surface mobility systems (Figure 6).

Develop selected critical technologies to enable sample return mission in 04–05 time frame and to provide indepth R&D data for operational propulsion system development and investment strategy.

Product Metrics

- Min T_{op} = -50°C
- $M_{dry}/M_{prop} \leq 0.7$
- F = 800 lb_f
- Zero venting LO_2 storage during cruise

State of the Art

- Min T_{op} = -0°C
- $M_{dry}/M_{prop} \leq 0.15$
- F < 800 lb_f or > 10,000 lb_f
- Thermodynamic venting for cryo propellant conditioning

	FY97	FY98	FY99	FY00	FY01
Warm Gas Pressure System Technologies	Warm Gas Catayst Breadboard System △				
Low-Temp Propellant and Lightweight Tank Technologies		Warm Gas Propellant Expulsion △			
Test and Evaluation		Hot-Fire Static Test of Full-Scale Breadboard △			

Figure 6. Planetary and Small Body Ascent Propulsion Systems

- **Deep Space Systems.** This program will develop, integrate, and test revolutionary technologies for solar system exploration. Emphasis will be on micro-avionics, autonomy, and computing technologies, as well as advanced power systems. Along with other technologies, these will be integrated as an advanced engineering-model flight system to form the basis for the new generation of survivable, highly capable microspacecraft (Figure 7). Future emphasis will be placed on the development of technology supporting in-situ missions, on technologies to continue the reduction of spacecraft mass, and in the development of revolutionary on-board computational capabilities.

Figure 7. Advanced Deep Space System Development

- **Astronomical Search for Origins Technology.** This program will develop critical technologies for studies of the early universe, star formation, and extra-solar planetary systems. Included are large lightweight deployable structures, precision metrology, optical delay lines, and other technologies for space-based interferometry. Also included are technologies such as inflatable structures and large lightweight optics required by many proposed missions and concepts (Figure 8).

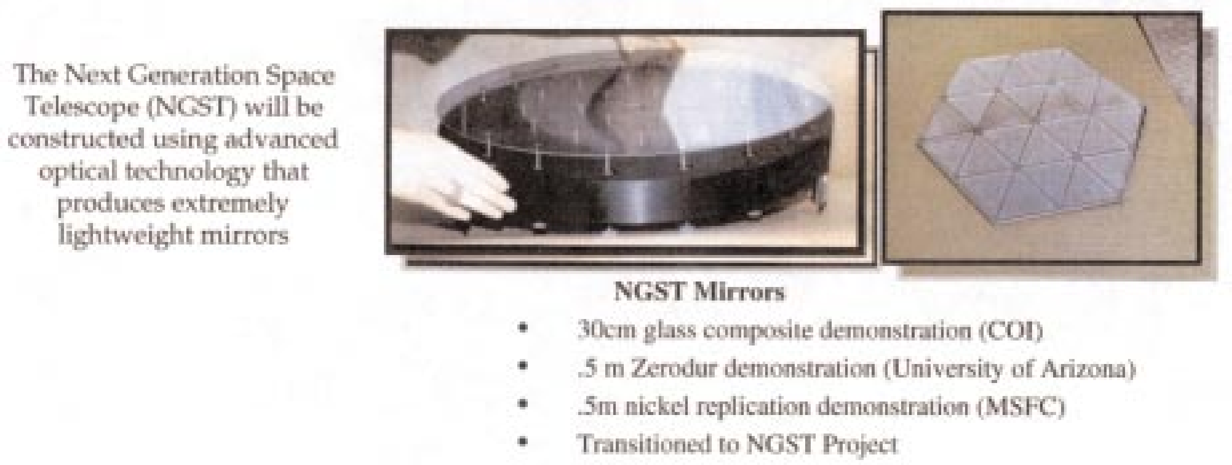


Figure 8. Lightweight Optics

- **Structures and Evolution of the Universe Technology.** This program will provide the technologies required for missions focused on understanding how the structure of our universe emerged from the Big Bang, how the universe is continuing to evolve, and what will be the fate of the universe. Examples of technology in this area include sensors, detectors, and other instruments, as well as extendable/inflatable structures and other instrument support systems (Figure 9).

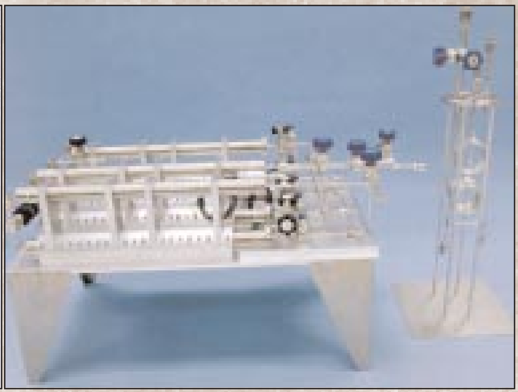
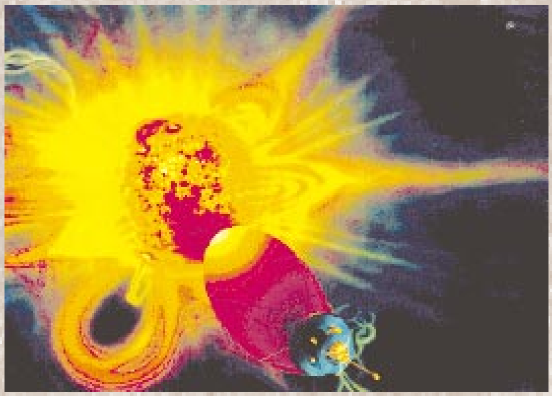
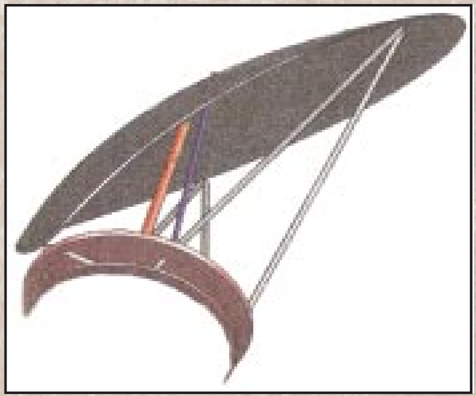


Figure 9. Ultra-sensitive detectors for astrophysics require cryogenic temperature and little or no vibration.

- **Sun-Earth Connection Technology.** This program will develop the technologies needed for missions focused on understanding long-term solar variability and how solar processes affect Earth. Technologies supported in this area include thermal shielding, integrated fields and particles sensors, and high-temperature solar arrays (Figure 10).





Carbon-carbon materials for extreme-temperature heat shields, efficient spacecraft radiators, and thermally stable optical benches.

Figure 10. Carbon-Carbon Materials

5. The **Flight Validation Program** completes the technology development process by validating technologies in space. The cornerstone of this program is the New Millennium program (NMP). New Millennium missions are driven by needs for technology validation, but they are also designed to return high-priority science data within cost and mission constraints. Additional flight validation platforms, including the International Space Station (ISS) and the Space Shuttle, balloons, sounding rockets, and

spacecraft or launch vehicle piggyback opportunities, may also be used as possible to validate technologies in the relevant space environment (Figure 11).

**New Millennium Program—
Deep Space-4**

NMP DS-4/Champollion will demonstrate new technologies needed for sample acquisition and return from a small body and will conduct *in-situ* measurements to validate the integrity of the sealed sample for return to Earth.

Figure 11. The cornerstone of the OSS Flight Validation Program, the New Millennium program, focuses on advanced development of those technologies requiring validation in the space environment. The New Millennium program is supported by both the Space Science and Earth Science Enterprises.

The programs above span the full spectrum of technology maturity, from fundamental seed ideas through flight validation, as shown in Figure 12. Technology products typically progress through the development cycle through multiple programs. For instance, an advanced concept, after proof-of-concept is demonstrated, may be transitioned into either the Cross-Enterprise or Core Technology Programs (depending on the breadth of applicability) for continued development, followed by system-level development and flight validation conducted in the focused programs and/or the Flight Validation Program.

Technology Readiness Levels (TRL)

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight-qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight-proven" through successful mission operations

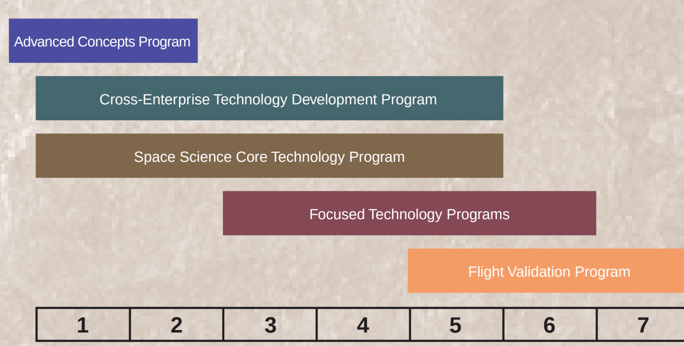
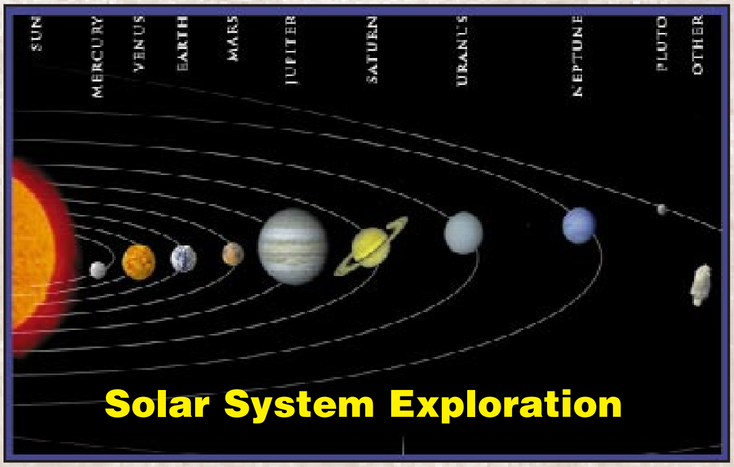
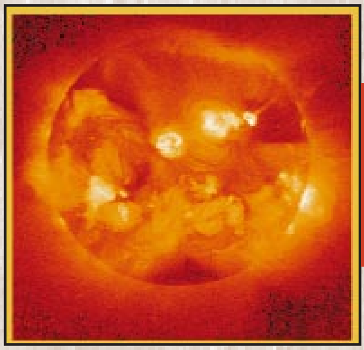
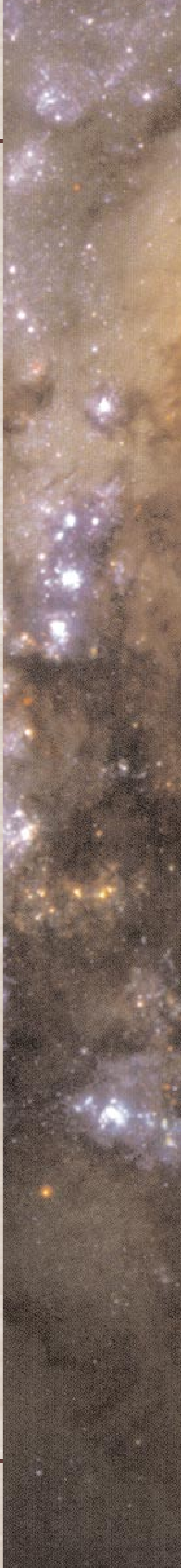


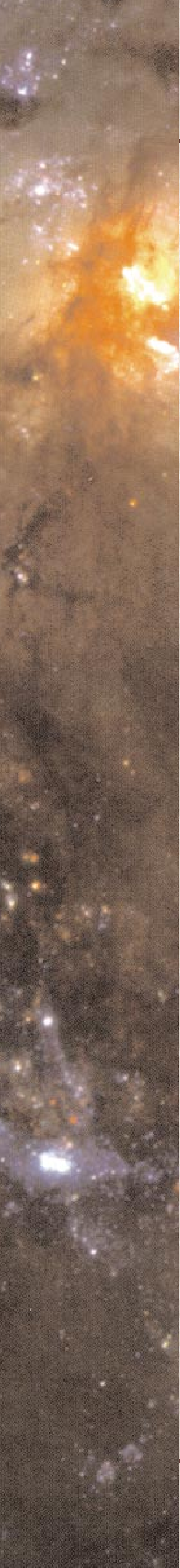
Figure 12. Technology Program Scope Versus Maturity





The Sun-Earth Connection





CURRENT TECHNOLOGY NEEDS

IV Space Science Enterprise Strategic Plans have generally looked 5 years into the future and undergone a major review and revision every 3 years. In 1997, we were challenged by the NASA Administrator to include a broad perspective of space science over the next 20–25 years. We have accordingly maintained a focus on a 5-year horizon (2000–2004) to support upcoming budget decisions, but we addressed this period in the context of much longer range goals (as shown in Appendix B).

To complete the plan, the OSS Board of Directors chartered a series of four mission roadmaps—one for each OSS science theme area. These roadmaps—developed by groups that included scientists, engineers, technologists, educators, and communicators of science—address science goals, strategies for achieving those goals, missions to implement these strategies, and technologies to enable the missions. In addition, each mission roadmap is accompanied by a technology roadmap describing the development activities needed to support the science program. Technology needs derived from these roadmaps represent the aggregate OSS customer needs, specifically driving the core and focused technology programs, and adding to the requirements being satisfied by the multi-Enterprise cross-cutting and flight validation programs and to those supplied by outside review bodies, such as those from the recent National Research Council report on “Space Technology for the New Century” (National Academy Press, 1998). Table 1 lists the current high-priority needs, integrated from these sources, being addressed by the OSS technology programs. The four OSS science theme roadmaps may be viewed at *http://www.hq.nasa.gov/office/oss/osshome*.

The OSS technology program responds to the broad technology requirements as outlined in the Space Science Enterprise Strategic Plan (see Table 1). To address these requirements, Table 2 maps the current technology needed to enable each mission. Table 3 provides a crosswalk of the current technology needed within the five program activities identified in Section III. Table 3 also provides measureable milestones against technology readiness levels as described in Figure 12 on page 9. Roadmaps of the next 25 years for these key technology capabilities are described more fully in Appendix B.

CURRENT TECHNOLOGY NEEDS

Advanced Structures Deployment and Control
- Ultra-precise deployment of lightweight structures
- Control of structural shape and vibration in space
- Precise pointing of large structures

Communications
- High-data-rate telecommunications technologies, including radio and optical transmitters and receivers
- Lightweight, low-power, robust electronics systems
- Lightweight antenna materials

Design Tools and Spacecraft Operability
- Advanced spacecraft design environment and rapid prototyping
- Integrated modeling of spacecraft and optical systems
- Ground information systems for low-cost spacecraft operations, data visualization, and analysis

Lightweight Optics
- Advanced segmented optical systems with high-precision controls
- Large lightweight mirrors
- Grazing incidence optics

Metrology
- Extremely precise measurement of orientations of in-space structures

Power
- High-efficiency solar arrays tolerant of extreme thermal and radiation environments
- New radioisotope power sources and conversion systems, with lightweight power for small vehicles
- Compact, rugged, high-energy-density energy storage systems capability of wide-temperature range operations

Sample Acquisition and Return
- Techniques for surface and subsurface sampling of planetary surfaces and small bodies, including drills, coring devices, scoops, and so on
- Sample handling and packaging techniques, with sample return capsules

Science Instruments
- New sensors and detectors for telescopes, interferometers, and remote and in situ instruments
- Highly integrated, lightweight instruments compatible with microspacecraft
- Coolers and other instrument support systems

Spacecraft Systems and Intelligence
- Advanced miniaturization and ruggedization of electronic and mechanical components
- New, highly autonomous and survivable spacecraft and computer architectures
- Lightweight, multifunctional structures

Transportation and Mobility
- Efficient in-space propulsion
- Mobility on or below planetary surfaces and within planetary atmospheres
- Information technologies
- Lightweight, high-temperature atmospheric entry, capture, and maneuvering systems

Table 1. High-Priority Needs of OSS Technology Programs
(as Described in the Space Science Enterprise Strategic Plan (November 1997))

Space Science Enterprise 1997 Strategic Plan Missions Technology Need	SIM	TPF	NGST	FIRST	GLAST	Constellation X-ray	Solar-Terrest.	Solar Probe	Europa Orbiter	Pluto/ Kuiper Express	Champollion/DS-4	Mars Surveyor
Advanced Structures Deployment and Control												
Large Lightweight Nonprecision Structures			Enabling				Enabling					
Lightweight Optically Precise Structures	Enabling	Enabling		Highly Enhancing	Highly Enhancing	Enabling						
Advanced Lightweight Materials			Enabling				Enabling	Enabling				
Communications												
Radio Frequency (RF) Microcommunications Systems							Highly Enhancing				Highly Enhancing	
Optical Communication Systems		Highly Enhancing	Highly Enhancing									
High-Rate RF Systems and Components		Highly Enhancing	Highly Enhancing				Enabling		Highly Enhancing			Highly Enhancing
Design Tools												
User Interfaces		Highly Enhancing					Highly Enhancing					
Collaborative Design Infrastructure		Highly Enhancing	Highly Enhancing			Highly Enhancing			Highly Enhancing	Highly Enhancing	Highly Enhancing	
Integrated Design and Simulation Tools	Highly Enhancing	Enabling	Enabling		Enabling	Enabling	Highly Enhancing	Highly Enhancing			Highly Enhancing	
Verification and Validation			Highly Enhancing						Highly Enhancing	Highly Enhancing		
Lightweight Optics												
Large Lightweight Mirrors		Highly Enhancing	Enabling	Enabling		Highly Enhancing						
Deployable Telescopes		Highly Enhancing	Enabling			Highly Enhancing						
Optical Control Systems	Enabling	Enabling	Enabling			Highly Enhancing	Highly Enhancing					
Science Instruments												
Submillimeter and Microwave Instruments				Enabling							Enabling	
Ultraviolet, Visible, and Infrared Sensors	Highly Enhancing	Enabling	Enabling				Enabling	Highly Enhancing	Highly Enhancing	Highly Enhancing		
Spectrometer and Radiometer Systems			Highly Enhancing						Highly Enhancing	Highly Enhancing		
High-Energy Instruments			Highly Enhancing		Enabling	Enabling	Enabling	Enabling				
Active Optical Sensing												
Radar Systems									Highly Enhancing			
In-Situ Systems							Highly Enhancing				Highly Enhancing	Highly Enhancing
Cryocoolers and Cryogenic Systems		Highly Enhancing	Enabling	Enabling		Highly Enhancing	Highly Enhancing					
Metrology												
Laser Metrology	Enabling	Enabling	Enabling									
Precision Active Optics	Enabling	Enabling	Enabling									
Ultrastable Structures	Enabling	Enabling	Enabling									
Sample Acquisition and Return												
Sample Selection and Acquisition Systems											Enabling	Highly Enhancing
Sample Preparation and Storage Systems											Highly Enhancing	
Power												
Energy Storage Systems							Enabling			Enabling		Enabling
Power Conversion										Enabling		
Photovoltaic Power Systems			Highly Enhancing				Enabling	Enabling				
Nuclear Power Systems									Enabling	Enabling		
Spacecraft Systems and Intelligence												
Advanced Spacecraft Architectures		Highly Enhancing					Enabling					
Instrument and Spacecraft Computing Systems	Highly Enhancing	Highly Enhancing	Highly Enhancing		Enabling		Highly Enhancing	Highly Enhancing	Enabling	Enabling		Highly Enhancing
Guidance, Navigation, and Control Sensors and Actuators	Enabling	Enabling					Enabling				Highly Enhancing	
Autonomous Science Algorithms and Architectures							Highly Enhancing					
Autonomous Operations Components and Algorithms		Enabling	Highly Enhancing		Enabling		Enabling					
Transportation and Mobility												
Onboard Spacecraft Propulsion							Enabling		Highly Enhancing	Highly Enhancing	Highly Enhancing	
Planetary Rover Systems and Components												Highly Enhancing
Aeronomy, Aerocapture, Aeroassist Systems							Highly Enhancing					
Planetary and Small Body Ascent Propulsion Systems											Enabling	

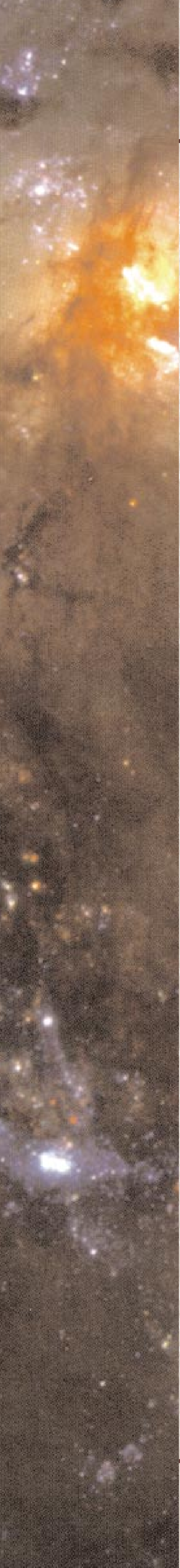
Enabling   Highly Enhancing

Table 2. Mission Technology Needs

Technology Need	Advanced Concepts Program	Cross-Enterprise Technology Development Program	Space Science Core Technology Program	Focused Technology Programs	Flight Validation Program*
Advanced Structures Deployment and Control					
Large Lightweight Nonprecision Structures	■	■		■	■
Lightweight Optically Precise Structures	■	■			
Advanced Lightweight Materials		■		■	
Communications					
Radio Frequency (RF) Microcommunications Systems	■	■			■
Optical Communication Systems	■	■			
High-Rate RF Systems and Components	■	■		■	■
Design Tools					
User Interfaces	■	■			
Collaborative Design Infrastructure	■	■			
Integrated Design and Simulation Tools	■	■	■	■	
Verification and Validation		■			
Lightweight Optics					
Large Lightweight Mirrors	■	■	■	■	
Deployable Telescopes	■	■		■	
Optical Control Systems	■		■	■	
Science Instruments					
Submillimeter and Microwave Instruments		■	■	■	
Ultraviolet, Visible, and Infrared Sensors		■	■		
Spectrometer and Radiometer Systems		■	■		
High-Energy Instruments	■	■	■	■	
Active Optical Sensing	■		■		
Radar Systems		■			
In-Situ Systems		■	■	■	■
Cryocoolers and Cryogenic Systems		■	■		
Metrology					
Laser Metrology				■	
Precision Active Optics				■	
Ultrastable Structures	■			■	
Sample Acquisition and Return					
Sample Selection and Acquisition Systems	■			■	
Sample Preparation and Storage Systems	■			■	
Power					
Energy Storage Systems	■	■		■	■
Power Conversion	■	■	■		
Photovoltaic Power Systems	■	■			■
Nuclear Power Systems	■			■	
Spacecraft Systems and Intelligence					
Advanced Spacecraft Architectures	■	■	■	■	
Instrument and Spacecraft Computing Systems	■	■	■	■	■
Guidance, Navigation, and Control Sensors and Actuators		■	■		
Autonomous Science Algorithms and Architectures	■	■		■	
Autonomous Operations Components and Algorithms	■	■	■	■	■
Transportation and Mobility					
Onboard Spacecraft Propulsion	■	■			■
Planetary Rover Systems and Components	■	■		■	
Aeronomy, Aerocapture, Aeroassist Systems	■				
Planetary and Small Body Ascent Propulsion Systems	■		■	■	

* Through DS-2, EO-2 only

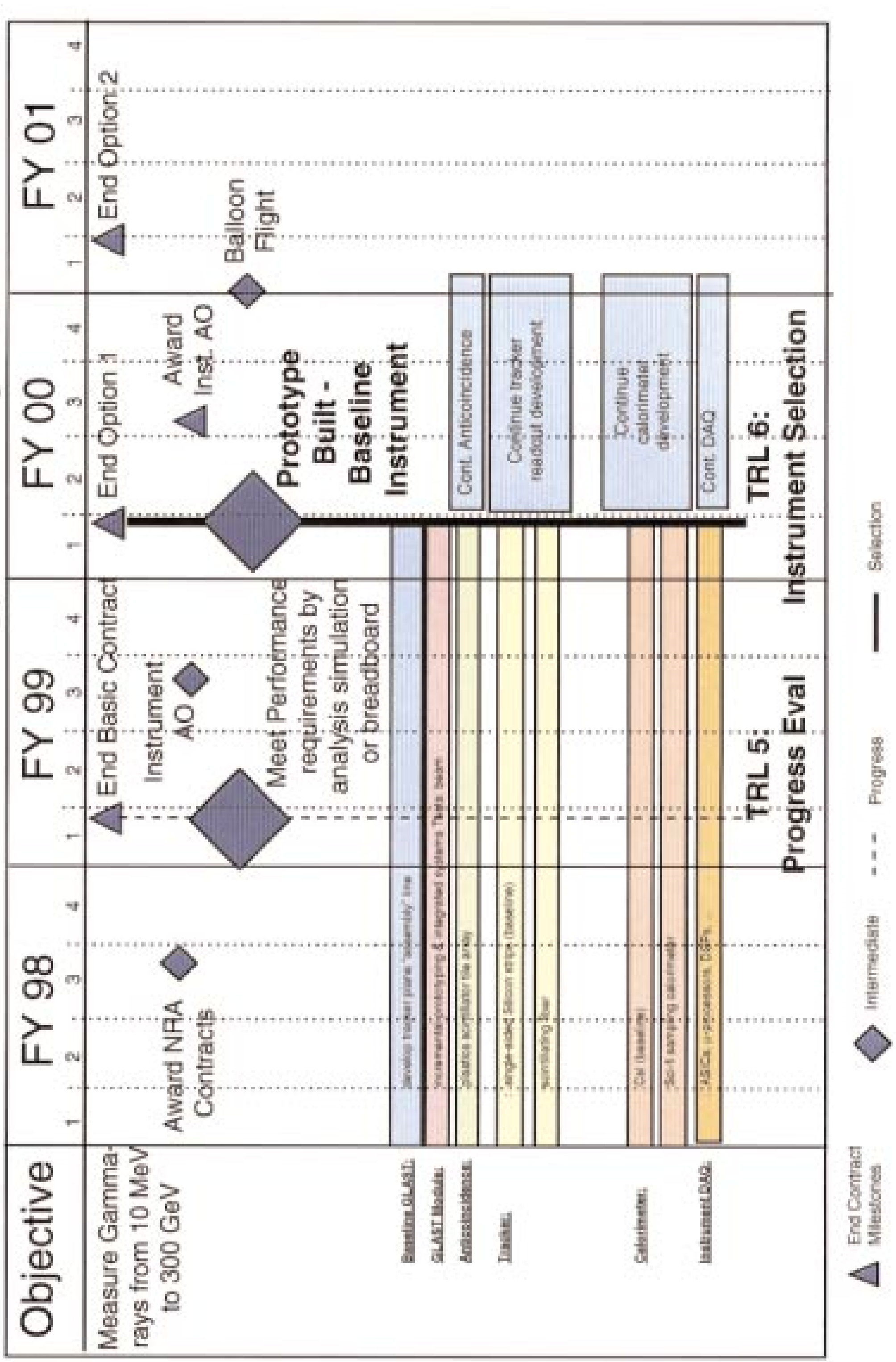
Table 3. Current Technology Program Activity



V The Space Science Enterprise recognizes that the successful infusion of technology into flight missions is a process that spans the life cycle of the mission, from embryonic formulation to completion. The Advanced Technology and Mission Studies (AT&MS) Division within the Office of Space Science was formed to ensure an intimate exchange through which the technology providers analyze the science goals and imagine innovative, revolutionary technologies to enable the missions. These ideas are subject to progressively more rigorous system, risk, and cost analyses as the mission concept matures through formulation, implementation, approval, and evaluation of the mission planning cycle, as outlined in NASA Procedures and Guidelines (NPG) 7120.5A and the Cross-Enterprise Technology Development Program Plan (Appendix A). In parallel, a technology program is planned that provides greater confidence in the technology's forecast capabilities through proof-of-concept models, laboratory testbeds, and, finally, space demonstrations if needed. The interchange between the technology program and mission studies is through written commitments of all the parties—technology providers, project users, and funding authority—to ensure stability and continuity of development. Management responsibility also shifts gradually so that, finally, the new technology deliverable to the project is funded and controlled by the project.

This technology analysis and annual allocation of technology funding is a critical function performed within the Enterprise's AT&MS Division. A multilevel technology management structure analyzes the Enterprise technology portfolio in the context of work performed elsewhere within NASA, work sponsored by other agencies such as the Department of Defense, industry technology development efforts, and developments conducted within the university community. This process provides for the analysis and comparison of ongoing work, current accomplishments, and projected milestones with the needs and requirements of the projects, preprojects and mission studies. The technology analysis structure also recommends budget adjustments and schedule modifications—within guidelines promulgated by the AT&MS Division—to reduce or eliminate discrepancies.

The long-term success of the technology program relies heavily on the quality of the ongoing program and the ability to validate revolutionary technology concepts. It also depends on how well these concepts are nurtured through the early phases and how quickly they are terminated if they are shown to be inappropriate for further development so that other more promising alternatives may receive funding. Experience shows that the technology development rates and termination rates vary with the discipline and with the style of the leading investigators. Part of the technology analysis process is devoted to understanding the expected development and termination rates for each discipline and to recommending an allocation of funds to high-risk, high-benefit—and often long-term—projects.



In the case of GLAST, an investment in technology is reviewed at each option to determine whether it has graduated to the next Technnology Readiness Level (TRL). After TRL 6, it is ready for downselection to technology used in flight validation.

VI

The Space Science Enterprise has reduced the average mission development time from over 9 years in the early 1990's to 5 years by the integration and early infusion of advanced technologies into missions. We expect to further reduce development time to less than 4 years, for missions planned in the years 2000 to 2004. OSS recognizes that the successful infusion of technology into flight missions is a process that spans the life cycle of the mission from embryonic formulation to completion. Further, the early phases of successful infusion of advanced technology are facilitated by a series of formal and informal interactions among the mission developers, scientific principal investigators, and technology providers. Joint activities and partnerships with universities, industry, and other Government agencies are particularly important to the advancement, integration, and infusion of advanced technology capabilities. Such partnerships permit the Space Science Enterprise to leverage funds to cross-fertilize ideas from different applications and to pursue different approaches simultaneously so that the most advanced technology can be identified quickly (Figure 13).

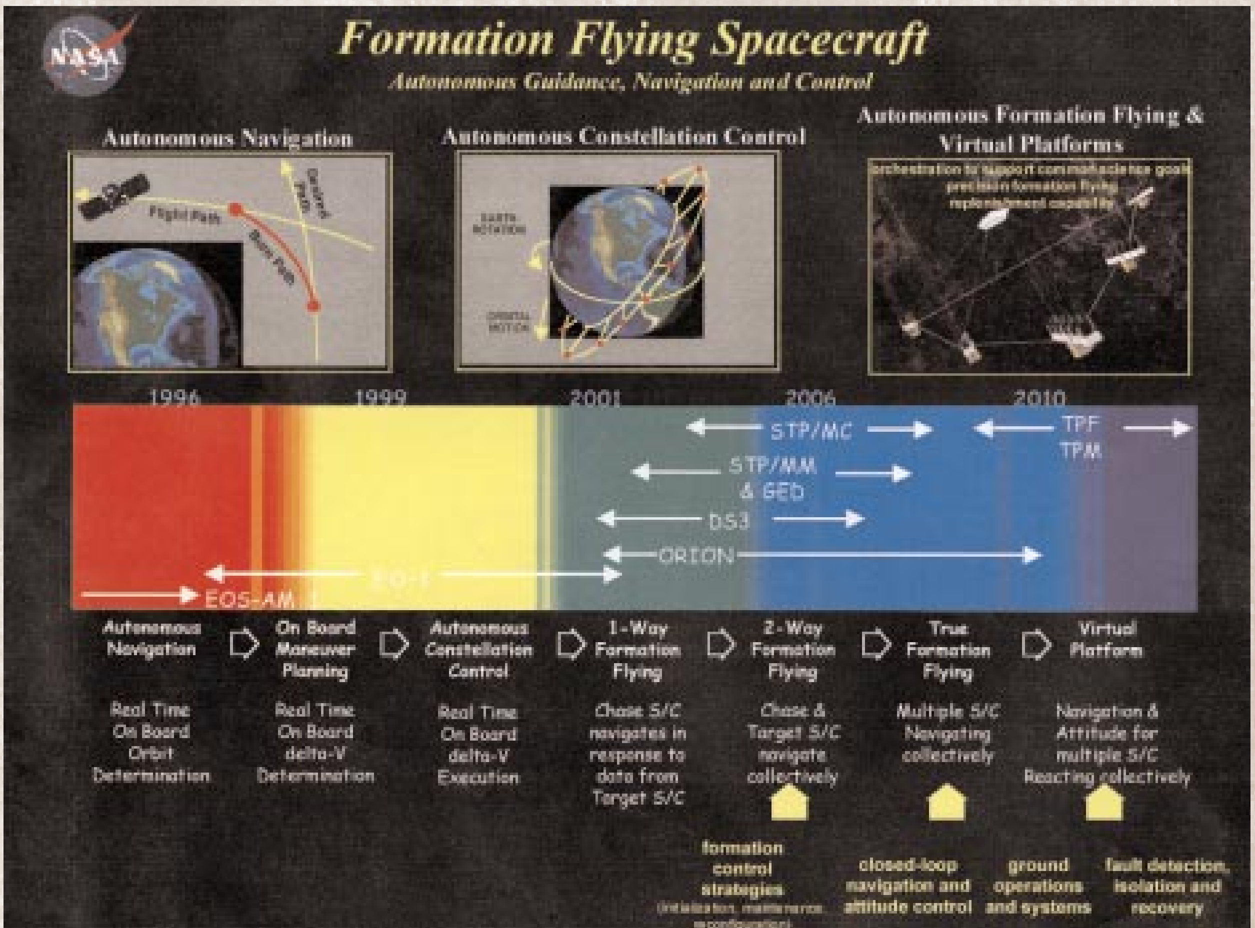


Figure 13. Each year, technology roadmaps are developed by teams of scientists, technologists, mission planners, and others to determine the appropriate strategic direction for technology developments in key areas. The roadmap shown here, for multispacecraft control, indicates desired developments for both the Space Science and Earth Science Enterprises over the next 20 years.

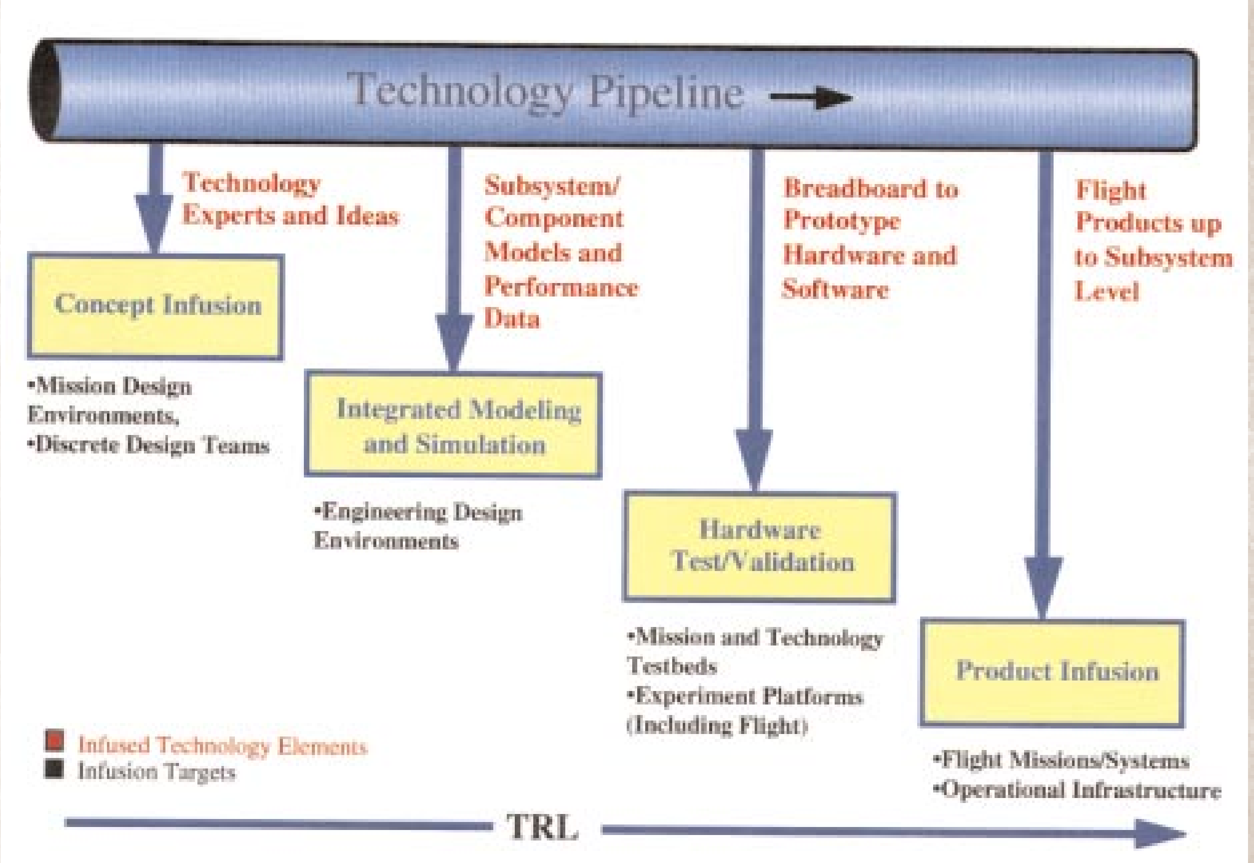


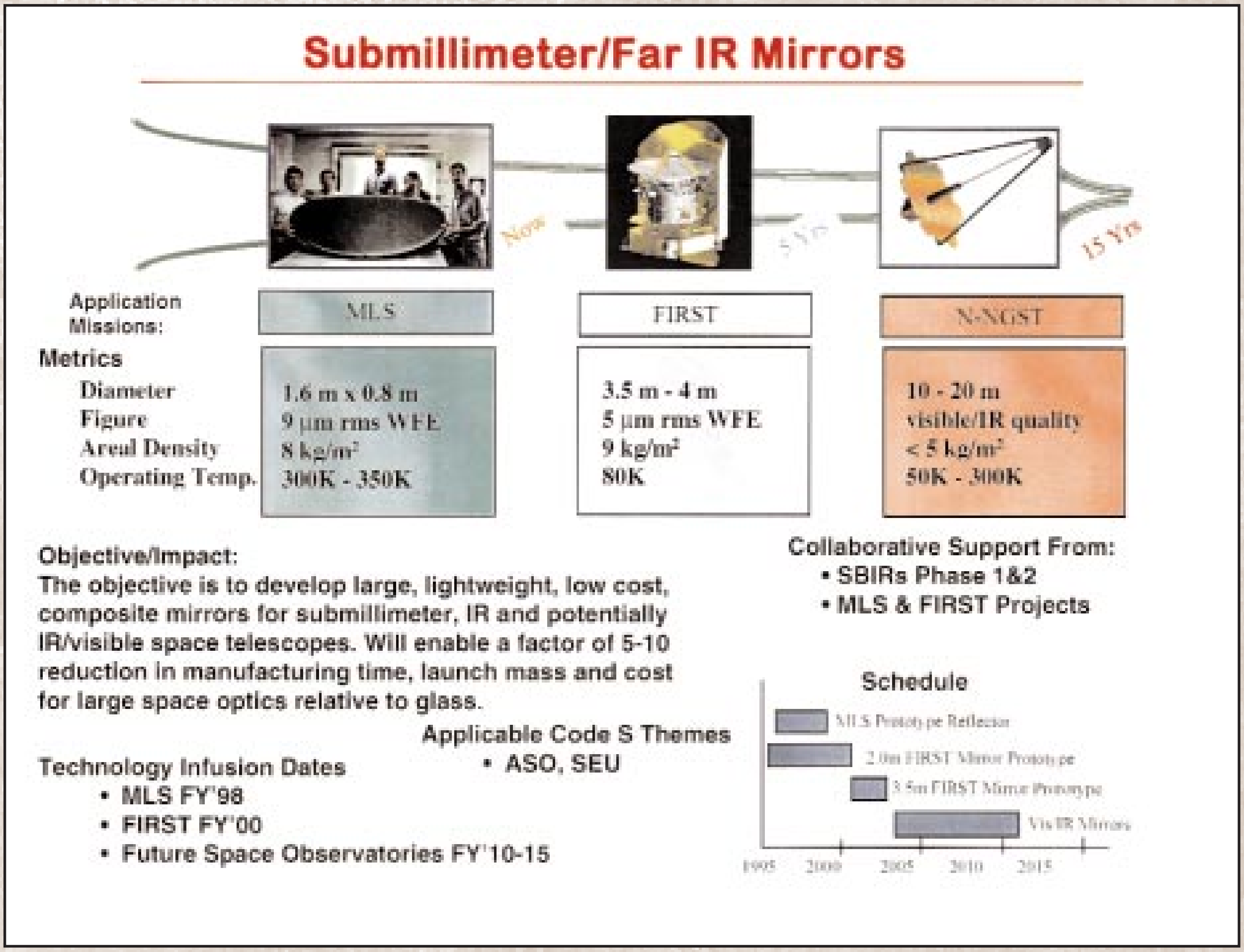
Figure 14. Technology Infusion—a Continuous Process

The process of infusion is a continuous one, taking place at all technology maturity levels (see Figure 12). It can be characterized at different levels:

a. At low TRL levels, technology concept infusion is accomplished after a technology is developed to a degree sufficient to introduce it into conceptual mission design studies or discrete technology trade studies. This allows the technology to be exercised in a relevant environment to determine its impact on a variety of missions or mission types (e.g., performance, cost) and to provide valuable feedback to the technologist regarding feasibility and design constraints. The infusion may be manifested as acceptance of the technology as an early baseline design carried by the mission(s) concepts and, as a result, acceptance as an enabling or highly enhancing technology need supported by one or more of a number of technology programs (see Table 3). Increasing emphasis will be placed in the future on incorporating a larger number and variety of technology concepts into these studies from both within and outside NASA (e.g., industry, universities, and other Government laboratories and agencies), as it represents the initial entry point for new technolgoy ideas.

b. At TRL 3/4, when the technology has reached a proof-of-concept level, the infusion of physical models and performance data into the mission design environments at the space science mission Centers allows a level of confidence in the technology to be developed that is necessary to baseline the technology into more mature mission designs (e.g., Formulation). Infusion at this point might result in the beginning of transition into a focused technology program, supporting advanced development into specific missions.

c. As the technology matures further (TRL 4/6), hardware and software components and/or subsystems become available for infusion and delivered and tested on various technology testbeds, environmental test facilities, and mission testbeds. At this point, the technology is physically exercised in environments relevant to its eventual mission application. As a result, the transition from early technology program support into focused or flight validation programs support accelerates as the mission(s) "pull" the technology into more mature flight-capable configurations.


Submillimeter/Far IR Mirrors
Now
5 Yrs
15 Yrs
Application Missions:
MLS
FIRST
N-NGST
Metrics
Diameter
Figure
Areal Density
Operating Temp.
1.6 m x 0.8 m
9 µm rms WFE
8 kg/m²
300K - 350K
3.5 m - 4 m
5 µm rms WFE
9 kg/m²
80K
10 - 20 m
visible/IR quality
< 5 kg/m²
50K - 300K
Objective/Impact:
The objective is to develop large, lightweight, low cost, composite mirrors for submillimeter, IR and potentially IR/visible space telescopes. Will enable a factor of 5-10 reduction in manufacturing time, launch mass and cost for large space optics relative to glass.
Collaborative Support From:
• SBIRs Phase 1&2
• MLS & FIRST Projects
Applicable Code S Themes
• ASO, SEU
Technology Infusion Dates
• MLS FY'98
• FIRST FY'00
• Future Space Observatories FY'10-15
Schedule
MLS Prototype Reflector
2.0m FIRST Mirror Prototype
3.5m FIRST Mirror Prototype
Vis/IR Mirrors
1995
2000
2005
2010
2015

VII The Space Science Enterprise is committed to the principles of open competition and merit review as a key to excellence. Early fundamental technology research will be selected through open, peer-reviewed competition. The later stages of technology development will be regularly reviewed for merit by independent panels of experts.

Partnerships with industry, universities, and other Government agencies will ensure that the revolutionary developments resulting from this program will be infused into the U.S. economy via a pathway of new products, new commercial applications, and enhanced competitiveness for the benefit of the entire Nation.

Industry has made and will continue to make significant contributions to the planning, development, and implementation of Space Science Enterprise missions and research programs. Industry continues to play a critical role in the design, engineering, manufacture, construction, and testing of both large and small space missions; in the design, development, testing, and integration of advanced instruments; and in the development of advanced spacecraft, instrument, mission operations, and information system technologies. Many industry capabilities have been developed for industry's commercial applications with DOD or NASA core technology support. The resulting extensive industrial space infrastructure is available for use by the space science research community. The establishment of partnerships with industry will allow participants in the Space Science Enterprise to better use the experience and the capabilities of the industrial sector (Figure 15).

Figure 15. Industry continues to play a critical role in the design, engineering, manufacture, construction, and testing of both large and small space missions.

TECHNOLOGY DEVELOPMENT AND PARTNERSHIPS

The trend toward smaller, more frequent, and lower cost missions has allowed universities (frequently in partnerships with industry) to take on responsibility for the design, development, and operation of entire missions, rather than just the development of individual instruments on larger NASA-developed missions.

Opportunities are vigorously pursued to collaborate with other Government agencies with similar objectives. The formation of technology development partnerships is an important goal of the Space Science Enterprise. DOE, DOD, and other agencies such as NOAA share many needs and capabilities with NASA. NASA works closely with all these agencies to identify shared needs and opportunities for synergistic technology development to maximize the value provided to the American public.

Partnerships with other NASA Enterprises are also essential to the Space Science Enterprise strategy. The Space Science Enterprise works with the Earth Science, Human Exploration and Development of Space, and Aeronautics and Space Transportation Technology Enterprises to coordinate and optimize their technology programs in areas of common interest or synergy.

The reliance on the identification, development, and utilization of advanced technology to dramatically lower instrument, spacecraft, and mission operations costs requires strong partnerships between industry and the Space Science Enterprise. Strong partnerships are also important for facilitating the transfer of NASA-developed technology to industry and, in so doing, realizing the commercial potential of these technologies and contributing to the long-term capability and competitiveness of American industry.

VIII Technology metrics are aligned with science and technology objectives. The metrics chosen depend on the maturity (or Technology Readiness Level) of the technology. Early in the development cycle, we can ask the question: How *effective* are the technology programs?

- Performance improvement
- Cost reduction potential
- Schedule or risk reduction potential

These elements are generally normalized by funding investment (benefit/cost measure). Later in the development cycle, we ask the question: How *efficiently* are the technology programs managed?

At this stage of development, metrics focus on performance and efficiency of the technology program

- Time to validation and time to infusion (incorporation into mission baseline design)
- Percentage of tasks/products carried from proof-of-concept successfully through validation and infusion
- Mission/project co-funding (partnerships within or outside NASA)

Technology Program Metrics

Metrics employed vary by maturity of technology program

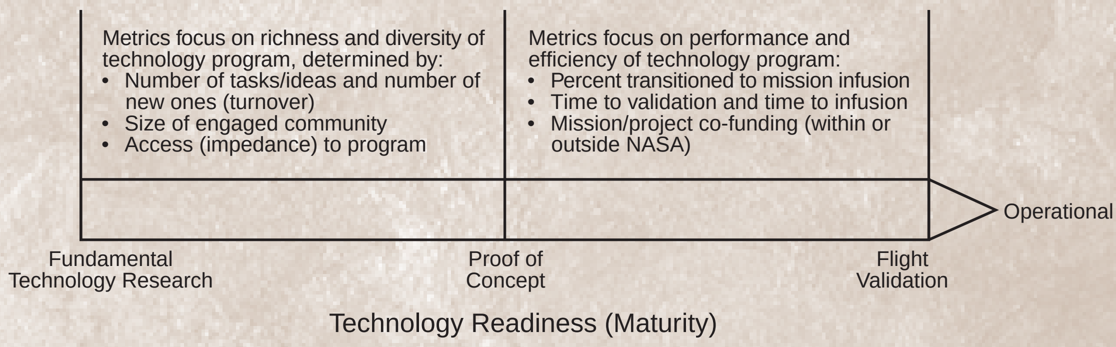
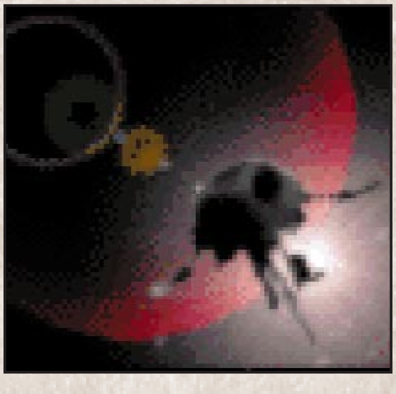


IMAGE AND STUDY A PLANETS AROUND OTHER STARS

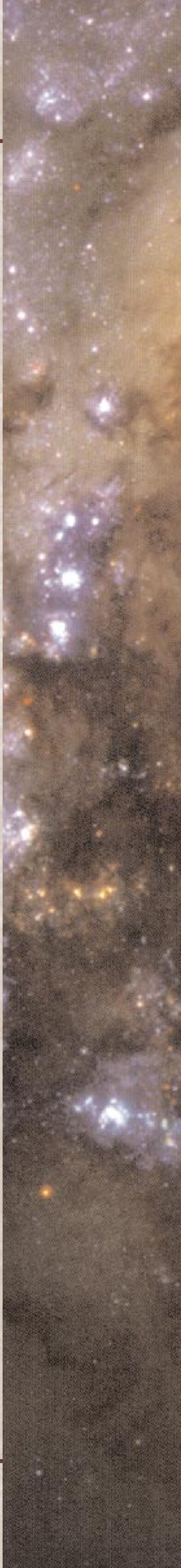
LOOK FOR EVIDENCE OF LIFE ELSEWHERE IN THE SOLAR SYSTEM

READ THE HISTORY AND DESTINY OF THE SOLAR SYSTEM



SEND SPACECRAFT TO A NEARBY STAR

CONDUCT A PROGRESSIVE AND SYSTEMATIC PLAN OF HUMAN EXPLORATION BEYOND EARTH ORBIT



IX

The past 2 years have witnessed a significant change in project development at NASA. The “faster, cheaper, better” approach has been embraced and is now entrenched in the thinking of those who execute the projects. It is concurrently being embraced by those who envision future missions. Thus, it is no less significant that an integrated approach to mission vision and concept development has been established. Space scientists, mission designers, and technology providers are working closely to create exciting and challenging concepts that border on science fiction. This interplay between scientists who inspire the technologists and technologists who broaden the vision of what may be possible for science is unprecedented and provides the rational for this integrated technology strategy. Even more spectacular concepts will most certainly emerge in the next phase of Space Science Enterprise strategic planning, and this technology plan will continue to reflect these changes (Appendix D). The best is yet to come!

NASA Cross-Enterprise Technology Development Program Plan

The NASA Cross-Enterprise Technology Development Program (CETDP) is responsible for developing critical space technologies that enable innovative and less costly missions and enable new mission opportunities through revolutionary, long-term, high-risk, high-payoff technology advances. The Program serves four Primary Customers: the Earth Science Enterprise (ESE), the Human Exploration and Development of Space (HEDS) Enterprise, the Space Science Enterprise (SSE), and the Office of the Chief Technologist's (OCT) Strategic Technology Areas. Cross-Enterprise technology is defined as long-range strategic technologies that have broad potential to span the needs of more than one Enterprise. Technology needs are identified and prioritized by each of the Primary Customers. While concerned with the Primary Customer's needs, CETDP is also expected to fund high-risk controversial technologies that will revolutionize NASA. These technologies may not have broad customer support at initial inception.

The CETDP is a NASA-wide activity managed through the Office of Space Science by the Advanced Technology and Mission Studies (AT&MS) Division. Program management for CETDP is distributed (multi-Center) and draws on expertise throughout the Agency. The Program is broken into two distinct components: the formulation component and the implementation component. Each component has a single lead: a Formulator, who plans the Program while maintaining awareness of emerging technologies, and an Implementor for Program execution and performance monitoring. Both of these activities are conducted concurrently throughout the year. The Director of AT&MS will assign the roles of Formulator and Implementor to specific NASA Field Centers (defined in this plan as including the Jet Propulsion Laboratory) and will review the assignment on an annual basis. The plan facilitates a team environment to support the technologists with enough freedom to produce revolutionary technological advances. The Program's technology products are developed by industry, universities, and NASA Field Centers.

The CETDP is managed in accordance with the NASA Procedures and Guidelines (NPG) 7120.5A Handbook as tailored to fit the CETDP. The Program annually reports to the Agency Program Management Council (PMC) and provides them with the results of an Independent Annual Review (IAR). The IAR reviews the current status of commitments (performance, cost, and schedule) against those described in the Program Commitment Agreement (PCA).

Program formulation is conducted annually in connection with the Program Operating Plan (POP) cycle; however, the Program maintains the flexibility to incorporate new technology tasks at anytime throughout the year. Strategic direction for the CETDP is guided by the NASA Strategic Plan, NASA Technology Plan, and Primary Customers' priorities. The Formulator has the responsibility of understanding technological barriers to Enterprise performance and performance targets and characterizing the technology strategies and investments of NASA, industry, and other Government agencies. It is within this integrated technology context that the CETDP is developed. A heavy emphasis is placed on a systems analysis approach to support strategic investment and the use of an annual general solicitation to capture a wide range of ideas at low Technology Readiness Levels (TRLs). The primary focus of the CETDP is to fill the front end of the

”technology pipeline” (low TRLs) with technologies capable of supporting revolutionary advances. Maturing technologies (higher TRLs) will be retained by means of partnering with the Primary Customers through Technology Cooperation Agreements (TCAs).

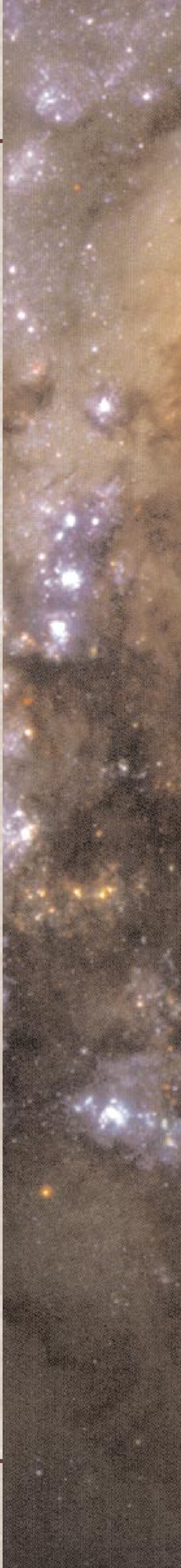
The Implementor executes the Program according to guidelines in the Implementation Plan. The CETDP is divided into project-level divisions called Thrust Areas. Each Thrust Area is managed by a Thrust Area Manager (TAM). The TAMs work with the technologists in a team environment to support formulation activities and produce technology products. The Implementor uses an Agency-level matrix-management approach, selecting TAMs from different NASA Field Centers.

The CETDP plays an important role in defining and maintaining core competencies in technology across the Agency. In general, the research Centers—Ames Research Center (ARC), Langley Research Center (LaRC), and Lewis Research Center (LeRC)—are the primary participants in developing technologies at low TRLs, supporting formulation, managing technology tasks, and developing partnerships with external organizations. The Primary Customers through the mission Centers—Goddard Space Flight Center (GSFC), Jet Propulsion Laboratory (JPL), Marshall Space Flight Center (MSFC), and Johnson Space Center (JSC)—are responsible primarily for transitioning low TRL developments to higher TRLs and integrating them into their missions.

This Program plan states the objectives and scope of the CETDP, describes the roles and responsibilities of key positions, and defines processes and controls used to manage the Program.

Key Technology Capability Roadmaps: Performance, Products, and Using Missions vs. Time

Time Horizon	Now	5 Years	10 Years	25 Years
Advanced Structures Deployment and Control	• Many low to moderate precision deployments already occurring • First flight test of microdynamics of deployable structures • 10^{-7}/deg C CTE of composite structures	• Flight deployment of 2–4-meter diameter structures • Shape control to 25µ RMS • NGST inflatable sunshield flight experiment • 5% structural damping lowest 20 modes • Enabling for Origins and SEU missions	• Flight deployment of 8m to 10m diameter structures • Control structure to 25µ RMS • 10^{-8}/deg C CTE of composite structures • Enabling for Origins and SEU missions	• Flight deployment of 20m to 25m diameter ultra light structures • Control shape to one micron RMS error for 25m diameter ultra light structures • 10^{-9}/deg C CTE of composite structures • Enabling for Origins missions
Communications	• Pathfinder: 10kbps from Mars for high-resolution color imaging • 30cm X-band S/C antenna • 70m ground antenna	• 1Mbps from Mars for HDTV • 30cm optical S/C telescope • Lightweight, low-power, robust communication electronics • Lightweight antenna materials • Enhancing technology for all missions	• 100Mbps from Mars approaching IMAX quality • 50cm optical S/C telescope • 10m ground receiving telescope • Lightweight, low-power, robust communication electronics • Lightweight antenna materials • Enhancing technology for all missions	• 10Gbps from Mars for Mars trunk line integrating orbiter, lander and rover data • 100cm optical S/C telescope • 10m ground receiving telescope • Lightweight, low-power, robust communication electronics • Lightweight antenna materials • Enhancing technology for all missions
Design Tools Spacecraft Operability	• Skunk works • Co-located teams • HW/SW breadboard and test	• Collaborative engineering • Tele-engineering • Model-based design • Benefits all missions	• 3-D real-time model-based design • Design visualization • Distributed engineering • Benefits all missions	• S/C design synthesis • Quick turn-around design • Formal verifications • Benefits all missions
Lightweight Optics	• HST mirror at 250kg/m^2 • SIRTF prototype at 25kg/m^2 • Segmented optical systems of 0.3–2m at 15kg/m^2 • Shell x-ray mirrors, 15 arc-sec HPD, 1,500kg, 0.7m diameter	• Segmented optical systems of 2m–4m diameter • Precision optical control to 150nm • Large lightweight mirrors of 2m diameter at 15kg/m^2 • Enabling for Origins missions	• Segmented optical systems of 8 to 10m diameter • Precision optical control to 50nm • Large lightweight mirrors of 4m diameter at 15kg/m^2 • Enabling for Origins missions • Enabling for NGST • X-ray mirror detectors, 5 arc-sec HPD, large area, lightweight, medium resolution, enabling for Constellation-X	• Thin-film transmissive optics of ≥24m aperture • Segmented optical systems of ≥20m diameter • Inflatable reflective optics of ≥25m aperture • Precision optical control to 30nm • Large lightweight mirrors of 4m diameter at 1kg/m^2 • RMS figure good enough for optical imaging • Enabling for Origins and SEU missions
Metrology	• Lab testbeds at one micron absolute and 250pm relative precision over 1-meter lengths	• Image-based wavefront sensors for infrared telescopes • 50pm relative metrology over 10m lengths • Enabling for Origins missions	• Image-based wavefront sensors for visible telescopes • 50pm relative metrology over 100m lengths • Enabling for Origins missions	• 50pm relative metrology over tens of km lengths • Enabling for Origins missions



Key Technology Capability Roadmaps: Performance, Products, and Using Missions vs. Time (continued)

Time Horizon	Now	5 Years	10 Years	25 Years
Power	• 18% efficiency, 50w/kg solar cells • 50Whr/kg Ni-H_2 batteries • 5W/kg @ 855W RTGs • 32kg Pu O_2 RTG fuel (Cassini) • Tolerant of Jupiter radiation belts • Beneficial for all missions	• 25% efficiency, 100w/kg solar cells, all solar to 5AU for Champollion; inflatable panels • 100Whr/kg Ni-H batteries • 12W/kg @ 150W RTGs • <2kg Pu O_2 RTG fuel for X2000, Pluto, Europa • <10g Pu O_2 for Mars, Europa • Tolerant of Jupiter radiation belts, Mars poles • Beneficial for all missions	• 30% efficiency, 150W/kg solar cells, possible all solar outer planet flybys; inflatable panels • 150Whr/kg Ni-H batteries • 15W/kg @ 10W RTGs • <200g Pu O_2 RTG fuel for outer planet orbiters and probes • <10g Pu O_2 for Mars polar probes, Europa subsurface • Tolerant of Jupiter radiation belts, Mars poles • Beneficial for all missions • Nanosatellite power generation system	• >30% efficiency, 200W/kg solar cells, possible all solar outer planet orbiter; inflatable panels • <200Whr/kg from advanced Li polymer batteries • 20W/kg @ 10W RTGs • 100g Pu O_2 RTG fuel or light reactor for ~100s of AU, NEP • Tolerant of Jupiter radiation belts, Mars poles • Beneficial for all missions
Sample Acquisition and Return	• Mobile science labs with ~5 integrated instruments for planets, comets, space physics • Organic compound detection • Subsurface penetrators with high-G-tolerant instruments (Mars 98/01/03 and Champollion) • Comet coma sample return (Stardust)	• Mini-biochemistry labs: detect amino acid chirality; wet chemistry lab; MEMS sensors on a chip • Mini-geochronology sensor with miniature mass spec. and laser-ablated samples • Comet nucleus and asteroid sample returns • Enabling for Mars program	• Long-range airborne and surface integrated mobile science labs with up to ten physical, chemical and biological measurements at and below planet, satellite, asteroid, or comet surfaces • Rad hard electronics and sensors working at temperatures found on Mars, Venus, Titan, comets, and asteroids • Pristine rocks, soils from Mars, comets, asteroids • Smart instruments (with humans) for surveys • Enabling technology for Mars, Venus, Titan, and small bodies	• Long-lived mobile science labs capable of multidiscipline interactive measurements • Sophisticated data analysis, fusion, and information extraction • Multidimensional sensors on a chip using MEMS technology • Pristine samples of outer planets and their satellites • Smart autonomous instruments for surveys, and samplers (without humans) • Enabling for landers on solar system bodies
Science Instruments	• 100μ features for electromechanical systems • Integrated instrument suite with common electronics (DS-1 and MICAS at 12kg, 12W, $8M)	• 25μ features in electromechanical micro-instruments (e.g., hydrometer) • Optical and infrared space-based interferometry • Enabling for Origins and SEU missions • Silicon Strip Detector Tracker with larger detector size (6" wafers) and increased effective area for energies >1 GeV for GLAST mission • Cesium Iodide Calorimeter with an 80 crystal module packing and a dynamic range of 80 MeV–80 GeV for GLAST • Advanced Scintillating Fiber Tracker Calorimeter with a fiber output of 20 photons and a tracker conversion efficiency of 80% for GLAST	• 10μ devices used in electromechanical-optical instruments such as weather station • Higher resolution, wide bandwidth imaging and spectroscopy, SAR, and radar sounding • Inflatable structures and optics for sciencecraft • Matched electronic and sensor operating temperature for integration • Enabling for Origins and SEU missions • Large format, low noise near infrared and far-infrared detector enables NGST • High-resolution, large-area reflective gratings and matched resistive gate CCD detector system enabling for Constellation-X • Accelerometers with a sensitivity less than 10(-13)q at 300 seconds enabling LISA • Cryogenic coolers achieving ranges of 2–20 degrees K with little or no vibration, low power, and long life enabling NGST and Constellation-X	• Nanometer-scale optical, quantum, or biological devices • Integrated sensors from γ-ray to MW with automated analysis and event-driven response • Automated continuous surveys of solar system with <100kg S/C and 10W per suite • Enabling for Origins and SEU missions

Key Technology Capability Roadmaps: Performance, Products, and Using Missions vs. Time (continued)

Time Horizon	Now	5 Years	10 Years	25 Years
Spacecraft Systems and Intelligence	• Single spacecraft at 180kg • 0.5µ feature size with 5V rad hard • Card-based, backplane architecture • Subsystem boxes and cabling • 100kg avionics • Preprogrammed sequences	• Formation of S/C (virtual S/C) at 90kg • 0.35µ feature size with 3.3V rad hard • Reconfigurable and programmable logic gates • Multichip modules and multifunctional modules for power, comm., data • 3-D flex interconnects • 35kg avionics subsystem • Semi-autonomous planning and operations • Benefits all missionsj • Data Acquisition System, <125w, 100kHz enabling for GLAST	• Precision constellations of 40kg S/C over hundreds of km, with cm precision • 0.18µ feature size with 1V rad hard • Fault-tolerant, reconfigurable and programmable logic gates • 3-D stacked chips and multichip module systems • Avionics systems on a chip • 10–15kg avionics • Fully autonomous operations with decision making and fault tolerance • Benefits all missions	• Massive 3-D swarms of 1–10kg S/C (virtual presence throughout solar system) • <20nm single electron quantum devices • Molecular nano-technology • Biological computing • Bio-electronic-optical hybrid tech. • Integrated, intelligent, multifunctional, reconfigurable, ultralow power microsystems • <1kg integrated avionics • Thinking systems with onboard scientific and operational expertise • Benefits all missions
Transportation and Mobility	• ΔV of 2.1km/s for Cassini • Tens of meters range for Sojourner with 11.5kg mass • High-altitude, short-lived Venera balloons on Venus • Stereo HDTV on Pathfinder for science analysis • Real-time public image dissemination	• ΔV of 10–15km/s from multimission SEP • Solar sail of 20g/m^2 • Tens of km with 50% science payload for Mars rovers • 0.5kg nanorovers for comets, asteroids, or local Mars surface • Home broadcast of HDTV space images • Automatic real-time space images via Internet • Stereo HDTV for operations, sample arm, navigation • Lighter (TBD) high-temperature atmospheric entry systems • Beneficial to Mars, outer planet missions	• ΔV of 30km/s with advanced SEP • ΔV of 50km/s with 5g/m^2 solar sail • Enables multibody sample return • Megawatt EP to support piloted Mars missions • Mars mobile science labs with hundreds of km range • Subsurface explorers to several km depth on Mars, Europa • Scalable mass from 0.1 to 100kg • Aerobots circumnavigating Mars, Venus, Titan • Stereo IMAX-quality images for operations and science • Stereo HDTV to homes • Lighter (TBD) high-temperature atmospheric entry systems • Beneficial to Mars, outer planet missions	• 100km/s SEP • 1gm^2 solar sail • ΔV of 500km/s using antiproton-catalyzed microfission/fusion • Interstellar robotic missions and piloted exploration of solar system • Autonomous labs circumnavigating Mars and interacting with humans • Nanorover swarms with hundreds of km range • Europa ocean exploration • 4X resolution of home digital video • IMAX-quality stereo panoramas in home without viewing aids • Real-time “virtual” roaming on planet and satellite surfaces • Lighter (TBD) high-temperature atmospheric entry systems • Beneficial to Mars, outer planet missions

Reference Documents

1. Office of Space Science Strategic Plan, dated November 1997
   http://www.hq.nasa.gov/office/oss/strategy/1997/

2. Office of Space Science Integrated Technology Strategy, dated April 1974

3. National Aeronautics and Space Administration Cross-Enterprise Technology Development Program Plan, draft dated June 1998 http://ntpio.nasa.gov/sti.html

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7. National Aeronautics and Space Administration Strategic Plan
   http://www.hq.nasa.gov/office/nsp/cover.html

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9. Implementation Plan Office of the Chief Technologist
   http://www.hq.nasa.gov/office/codea/codeaf/plan.html

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Pioneering the Future

National Aeronautics and
Space Administration

Washington, DC 20546

NP-1998-10-243-HQ

Office of Space Science Technology Planning and Management

This Integrated Technology Strategy supporting the NASA Technology Implementation Plan, developed by the Office of the Chief Technologist, establishes the framework through which the Office of Space Science will satisfy stakeholder expectations. The Office of Space Science has specific responsibility within NASA for two areas:

a) All technology to enable and enhance scientific exploration and discovery in support of the Space Science Enterprises' four themes of sun-Earth connection, solar system exploration, structure and evolution of the universe, and astronomical search for origins.

b) Cross-Enterprise, common spacecraft-related technology supporting multiple missions across Enterprises to avoid duplication and exploit synergy (such as high efficiency solar arrays which support science as well as human exploration missions).

The process for an aggressive and carefully planned program of technology research, development, and utilization, in which mission concepts and supporting technologies are developed synergistically is displayed in Figure D1.

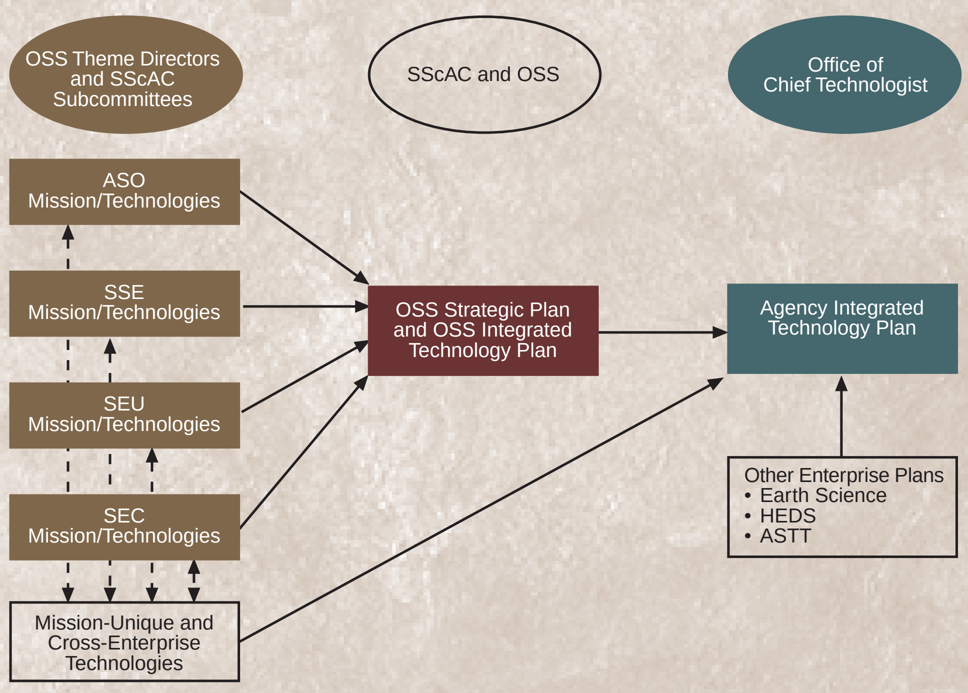

Figure D1. Space Science Strategic Planning and Integrated Technology Plans